A Section 508–conformant HTML version of this article
is available at https://doi.org/10.1289/EHP10399.

# Combined Sewer Overflows and Gastrointestinal Illness in Atlanta, 2002–2013: Evaluating the Impact of Infrastructure Improvements

*Alyssa G. Miller,[1] Stefanie Ebelt,[2] and Karen Levy[1,2]*

[1]Department of Environmental and Occupational Health Sciences, School of Public Health, University of Washington, Seattle, Washington, USA
[2]Gangarosa Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, Georgia, USA

**Background:** Combined sewer overflows (CSOs) discharge untreated sewage into surface and recreational water, often following heavy precipitation. Given projected increases in frequency and intensity of precipitation due to climate change, it is important to understand the health impacts of CSOs and mediating effects of sewerage systems.

**Objectives:** In this study we estimate associations of CSO events and emergency department (ED) visits for gastrointestinal (GI) illness among City of Atlanta, Georgia, residents and explore how these associations vary with sewerage improvements.

**Methods:** We estimate associations using Poisson generalized linear models, controlling for time trends. We categorized CSOs by overflow volume and assessed effects of CSO events prior to ED visits with 1-, 2- and 3-wk lags. Similarly, we evaluated effects of weekly cumulative precipitation greater than the 90th percentile at the same lags. We also evaluated effect modification by ZIP Code Tabulation Area (ZCTA)-level poverty and infrastructure improvement period using interaction terms.

**Results:** Occurrence of a large volume CSO in the previous week was associated with a 9% increase in daily ED visits for GI illness. We identified significant interaction by ZCTA-level poverty, with stronger CSO–GI illness associations in low than high poverty areas. Among areas with low poverty, we observed associations at 1-wk and longer lags, following both large and lower volume CSO events. We did not observe significant interaction by infrastructure improvement period for CSO– nor precipitation–GI illness associations; however, the number of CSO events decreased from 2.31 per week before improvements to 0.49 after improvements.

**Discussion:** Our findings suggest that CSOs contribute to acute GI illness burden in Atlanta and that the magnitude of this risk may be higher among populations living in areas of low poverty. We did not find a protective effect of sewerage system improvements. Nonetheless, observed reductions in CSO frequency may lower the absolute burden of GI illness attributable to these events. https://doi.org/10.1289/EHP10399

## Background

Climate change is projected to induce increased frequency and intensity of precipitation in many regions throughout the United States under both low and high emissions scenarios.[1,2] The southeastern United States, which is already vulnerable to flooding due to a combination of aging infrastructure, hurricanes, and other extreme precipitation events, has started to experience these climate related impacts in recent years. The average number of days with heavy rainfall has risen over the past decade and there has been a 16% increase in 5-y maximum daily precipitation for the region.[1] There is concern that these changes in precipitation patterns pose a direct risk to public health by overwhelming current water management systems.[3] Prior epidemiological research has reported associations between heavy precipitation and a variety of health outcomes, including gastrointestinal (GI) illness.[4–7] In Wisconsin, any rainfall was associated with an 11% increase in pediatric emergency department (ED) visits for acute GI illness,[8] and in Massachusetts, flooding events were associated with an 8% increase in GI infections.[9]

One exposure pathway that may contribute to the increased incidence of GI illness following precipitation is via municipal water conveyance systems, specifically for those municipalities with combined sewer systems (CSS). Rather than providing separate piping systems for rainwater runoff, domestic sanitary sewage and industrial wastewater, a CSS collects all waters into a single common pipe. Wastewater treatment plants (WWTPs) have strict flow limitations; therefore, during very high flows, such as following a heavy precipitation event, a portion must be diverted away from the WWTP and discharged directly to a nearby receiving water.[10] This discharge, prior to treatment, is termed a combined sewer overflow (CSO) event. CSO events can potentiate the impact of precipitation on the receiving water body. A recent study estimated that following heavy rain, occurrence of a CSO event led to 10 times more sewage contamination in surface waters than a heavy rain event alone.[11] Therefore, areas with CSS are especially vulnerable to the increased intensity of rainfall anticipated with future climate change, which would lead to larger volume CSOs, and consequently, greater volume of pollutants discharged to surface bodies.[11,12]

Prior environmental studies have documented decreased surface water quality following CSO events.[13–15] The occurrence of CSOs has been linked to increased levels of pathogens in receiving waterbodies, often surpassing guidelines set by the U.S. Environmental Protection Agency (U.S. EPA).[15,16] Pathogenic microorganisms found in CSO effluent include bacteria, viruses and protozoa such as *E. coli*, *Cryptosporidium*, *Salmonella*, *Giardia* and norovirus.[16] Overall, these types of microorganisms account for a significant portion of enteric illness in the United States.[16] Furthermore, a recent study has shown that bacteria in CSOs are often resistant to antibiotics, with the yearly discharge of antibiotic-resistant *E. coli* from CSO events 3.7-log larger than from WWTP effluent.[17] Routes of exposure to these pathogens following CSO events include ingestion (drinking water, cooking, etc.) or direct body contact (recreation) and subsequent incidental ingestion.[11] Because the CSOs of concern in our study are downstream of primary drinking water intake sites for metropolitan Atlanta, Georgia, it is likely that direct body contact and subsequent incidental ingestion is the primary exposure pathway of interest in our study region.[23] However, intrusion into the drinking-water distribution system downstream of treatment is

Address correspondence to Alyssa G. Miller, Department of Environmental and Occupational Health, University of Washington; address: 4225 Roosevelt Way NE, Seattle, WA 98105 USA. Email: agmill@uw.edu

Supplemental Material is available online (https://doi.org/10.1289/EHP10399).
The authors declare they have nothing to disclose.
Received 27 September 2021; Revised 15 April 2022; Revised 23 February 2022; Accepted 25 April 2022; Published 17 May 2022.

also a possible mechanism of exposure, and prior studies have suggested that contaminants released with CSOs may affect the quality of local drinking water.[5]

Water-based recreation in the metropolitan Atlanta area is popular; the nearby Chattahoochee River National Recreation Area has approximately 2.8 million visitors annually, 30% of whom participate in primary and secondary water-based activities such as swimming, tubing, kayaking, and fishing.[18] Based on the prevalence of pathogenic microorganisms in waterbodies, the annual probability of contracting GI illness among recreators in areas with CSO outfalls is estimated to be as high as 0.68, and even higher among vulnerable populations such as the homeless, according to a risk assessment performed by Donovan et al. in the Lower Passaic River in New Jersey.[16] This risk translates to a substantial health burden across the United States, with an estimated 50.95 million cases of GI illness due to water recreation annually.[19]

Although construction of CSSs is no longer permitted in the United States, nearly 860 municipalities throughout the country still rely on these systems, including many in the Southeast.[10] These systems can be a liability for cities: In the 1990s Atlanta lost a lawsuit based on the failing stormwater collection and treatment systems that resulted in poor water quality in the Chattahoochee River, a major source of drinking water and recreational activity in the Atlanta metropolitan area.[18,20] As a result, Atlanta was required to invest more than \$2 billion over 25 y in the city's CSS, including sewerage separation projects targeted at improving area water quality and reducing CSOs.[20] Although these improvements have resulted in an 80% reduction of bacteria levels in the Chattahoochee River, the potential protective effect of a reduction in CSO events on human health in the community has not been explored.[20]

A variety studies have linked occurrence of CSOs to increased concentrations of pathogenic microorganisms in nearby surface waters, but there has been less focus on examining the potential effects of CSOs on human health outcomes.[11–18] Nonetheless, some studies have indicated an increased risk for GI infections related to CSO events. For example, in a case–crossover study conducted in Cincinnati, Ohio, researchers identified a 16% increase in risk of ED visits for GI infections among children living within 500 m of a CSO outfall location 2 d after a CSO event.[21] In a similar study, children living in ZIP codes that used Lake Michigan as their drinking water source saw an additional 0.2 ED visits for GI illness in the 3–7 d following high volume CSO events in comparison with no events.[22] Finally, a recent study found that New England towns with CSS that discharge to drinking water sources experienced a 13% increase in GI infections following heavy precipitation events, whereas areas without CSS experienced no significant increase in risk.[5]

In this study, we characterized the association between CSO events and ED visits for GI illness among City of Atlanta residents, which is important to understand given the projected impact of climate change in the Southeast. We determined the time structure of CSO events, explored the impact of size of events, and identified populations at increased vulnerability to their effects. We hypothesized that days with any CSO event in the previous 1–3 wk would have a significantly higher rate of ED visits for GI illness in comparison with days with no events in the specified period, and that areas with high poverty would have increased burden (i.e., stronger associations) in comparison with areas with low poverty. CSO outfall locations in Atlanta are disproportionately distributed in areas with higher poverty (Figure 1); therefore, these communities may be more likely to be exposed to the contaminated water. Furthermore, socioeconomic disparities in health status have been well documented and could contribute to greater susceptibility to GI illness in these communities. To better understand exposure pathways, we additionally assessed differences in the CSO–GI association by season. Because water-based recreation is more common in the summer, we hypothesized that the CSO effect would be strongest in the May–September period.

We also explored differences in CSO–GI and precipitation–GI associations over time as infrastructure improvement projects were completed in Atlanta, to better understand the efficacy of stormwater infrastructure improvements to prevent GI illness. Because CSOs have been shown to potentiate the effect of heavy rainfall on surface water contamination, we hypothesized that the precipitation–GI association, but not the CSO–GI association, would be higher prior to improvements in comparison with the postimprovement period.[11]

## Methods

### *Data Sources*

Daily CSO event data for the City of Atlanta for the period 1 January 2002 through 31 December 2013 were obtained from the City of Atlanta Department of Watershed Management Quarterly Consent Decree Status Reports, available via the Consent Decree Document Repository.[23] Although the CSO data are available for more recent years, we chose to focus on the period for which we had reliable outcome data. These reports, published as PDFs, were converted to Excel using Docparser an online optical character recognition platform (accessed November 2019; https://docparser.com). Each quarterly report tabulated data on CSO events at each outfall location ($n = 7$ locations), including date and volume of each discharge and various associated water quality indicators, such as turbidity and fecal indicator bacteria. However, water quality data was inconsistent in the reports; therefore, we chose not to use these indicators as a focus of our analysis. CSO outfall locations in the City of Atlanta are shown in Figure 1. These data were used to calculate daily and weekly summaries of CSO effluent across the outfall locations. Daily precipitation data for the study period were obtained from the weather station at Atlanta Hartsfield Jackson Airport. Daily precipitation data were used to calculate weeklong cumulative sums of precipitation.

Periods of stormwater infrastructure improvements were determined using reports provided on the City of Atlanta Department of Watershed Management website.[24] Based on the available information on CSO projects (including sewer separation projects, CSO control tunnels, addition of control facilities), notice to proceed and date of substantial completion, we identified three distinct periods: before, during, and after improvements to infrastructure. The before period was defined as 2002–2005, the during period was defined as 2006–2008, and the after period was defined as 2009–2013.

Data on ED visits to metropolitan Atlanta–area hospitals were obtained for the 2002–2013 period. Specifically, patient-level electronic billing records data on ED visits were acquired directly from individual hospitals (for the period 2002–2004) and from the Georgia Hospital Association (for the period 2005–2013). These data have been previously used in multiple studies.[25–29] Data were restricted to patients with primary addresses within the boundaries of the City of Atlanta. Atlanta residence was determined by patient ZIP code, where any ZIP code covering City of Atlanta land was included. ED visits by Atlanta residents outside of the metropolitan Atlanta–area hospitals were not collected. We aggregated the patient-level data to daily counts of ED visits for GI illness, identified via primary and secondary *International Classification of Disease, 9th Revision* (ICD-9) diagnosis codes 001–009. Use of the ED data was in accordance with agreements with the hospitals and the Georgia Hospital Association, and this study was approved prior to its conduct by the Emory University institutional review board (protocol # IRB00045761).

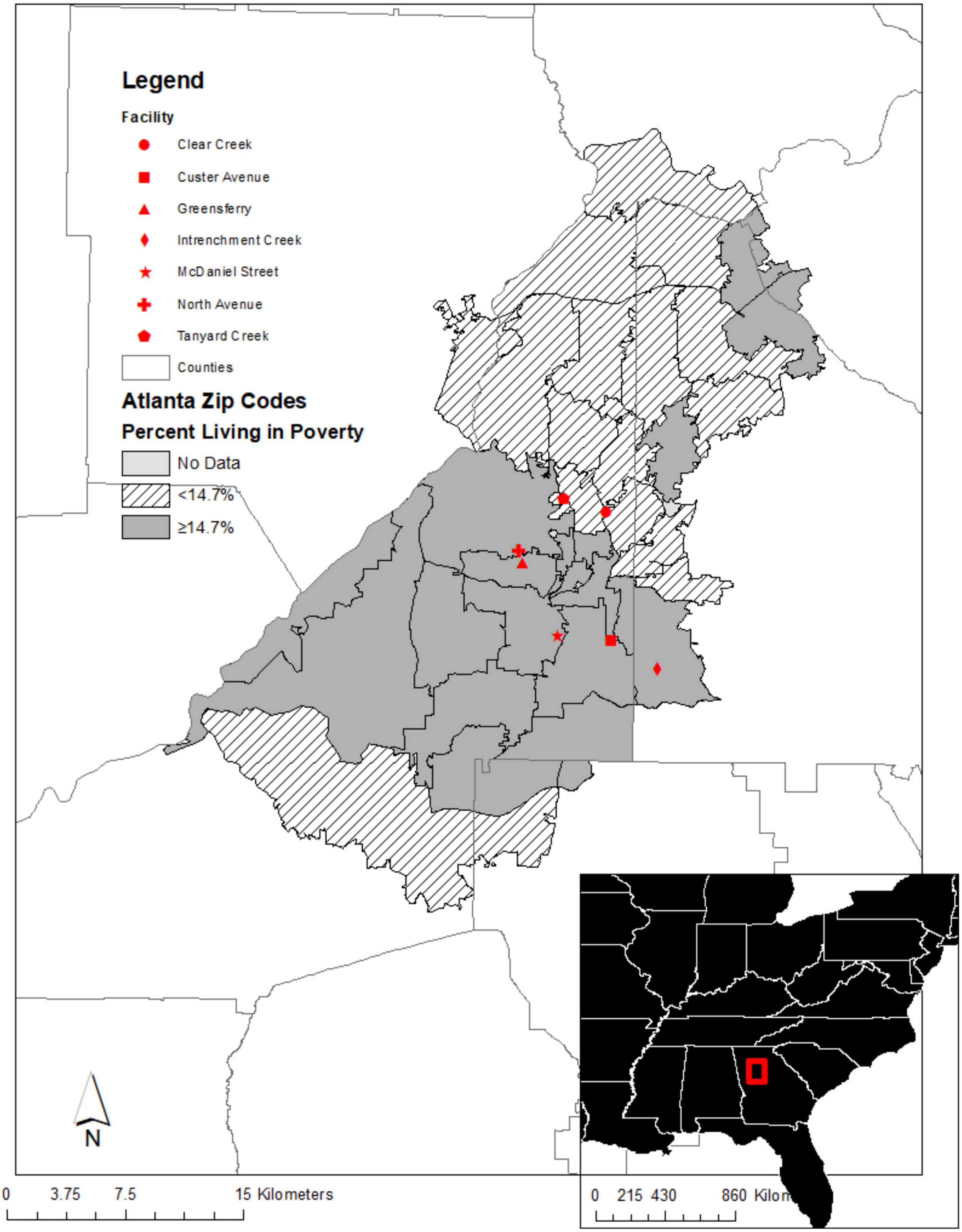


**Figure 1.** Distribution of poverty by ZIP code tabulation area (ZCTA) and combined sewer overflow (CSO) outfall locations in Atlanta, Georgia. ZCTA-level poverty determined by percent of residents in a ZCTA living below the federal poverty line during 2007–2011 (median = 14.7%) and dichotomized as above vs. below the median. CSO outfall locations as documented by City of Atlanta, Department of Watershed Management. Inset figure shows the relative location of Atlanta in the United States. Figure 1 was produced using ArcGIS software (Esri; Version 10.3).

Neighborhood-level socioeconomic status (SES) was obtained via the American Community Survey (ACS) 5-y (2007–2011) summary file.[30] Estimates of Zip Code Tabulation Area (ZCTA)-level percent of population living below the federal poverty line were used as a proxy for neighborhood-level SES to examine SES as an effect modifier. The continuous poverty variable was dichotomized to high and low poverty based on an *a priori* cut point above and below the median. In Atlanta, during the study period, the median percent of the population living below the federal poverty line was 14.7% (Figure 1).

Maps were created using ArcGIS software (Version 10.3) (Esri, Redlands, CA). All analyses were performed using SAS statistical software (Version 9.4) (SAS Institute, Inc.). We examined univariate statistics for CSO events, precipitation, and the daily count of ED visits for GI illness, as well as correlations between these variables using Pearson and Point-Biserial correlation statistics where both variables are continuous or where one is dichotomous, respectively. Daily and weekly time-series plots of ED visits for GI illness, total volume of CSO discharges and precipitation were evaluated across the study period and by infrastructure improvement period.

### *CSO–GI Illness Models and Submodels*

Multivariable analyses were conducted using Poisson generalized linear models allowing for overdispersion. Primary models assessed the citywide effect of CSO events on daily ED visits for GI illness. The basic form of the model was:

$$Log\,(ED_t) = \alpha + \beta_i \mathrm{CSO}_{ti} + \gamma_i precip_{ti} + \gamma_4 weekend_{ti} + \gamma_5 season_{ti} + \gamma_7 holiday_{ti} + \gamma_j hosp_{ti} + ns(t, degrees\ of\ freedom = 4), \quad (1a)$$

where $\mathrm{ED_t}$ refers to the count of the ED visits for GI illness on day $t$. The dichotomous variable $CSO_{ti}$ represents the occurrence of any CSO event in the 1 wk prior (lag 0–6 d summary), 2 wk prior (lag 7–12 d summary), or 3 wk prior (lag 13–20 d summary). We considered the occurrence of a CSO event over a period of 21 d because incubation time and symptomatic periods for GI illnesses has been shown to last up to 3 wk.[31] We examined this lag time by individual week to identify windows corresponding to particularly high risk. We considered models that included the continuous measure of weekly sum of precipitation ($\mathrm{precip}_{ti}$) at the same lag as the CSO event terms and compared these models to models that did not include precipitation as a covariate to identify potential confounding by precipitation. We identified precipitation as a potential confounder due to its causal effect on CSOs and reported independent associations with GI illness.[4,7,8] All models included indicator variables to control for weekends, season (winter: December–February; spring: March–May; summer: June–August; autumn: September–November), federal holidays, and periods of hospital participation (*hosp*), as in previous time-series analyses using these ED visit data.[28,29] Hospital participation was included to control for periods in which a given hospital was not contributing ED visit data to the study, therefore reducing the overall number of observed cases. Long-term time trends were additionally controlled with cubic splines with seasonal knots with 4 degrees of freedom. We estimated rate ratios (RR) for the effect of any CSO event in the given week, in comparison with no event, by exponentiating the beta coefficient (β) from these models.

Second, to evaluate the effect of CSOs on ED visits for GI illness allowing for different impacts by volume of event, we modeled:

$$Log\,(ED_t) = \alpha + \beta_{1i} small_{it} + \beta_{2i} med_{it} + \beta_{3i} large_{it} + \gamma_i precip_{ti} + \gamma_4 weekend_{ti} + \gamma_5 season_{ti} + \gamma_7 holiday_{ti} + \gamma_j hosp_{ti} + ns(t, degrees\ of\ freedom = 4), \quad (1b)$$

where all variables are as specified as in Equation 1a. Dummy variables were created using volume data from CSO events in Atlanta from 2002 to 2013 indicating small volume CSO events (i.e., events <25 th percentile of volume), medium volume events (i.e., events 25th–74th percentile of volume), and large volume events (i.e., events ≥75 th percentile). Volume categorizations were based on the summation of effluent volume across outfall locations in a day rather than individual discharges. Each of these variables was summed across the week prior, 2 wk, and 3 wk to create an indicator for any CSO event of a given level in the specified week as in the primary model. We estimated the individual effect of large volume events, medium volume events and small volume events in the week prior, 2 wk prior, and 3 wk prior in comparison with no event. Again, we considered models that controlled for weekly sum of precipitation and those that did not to identify potential confounding.

We carried out a sensitivity analysis to assess the importance of the volume cutoffs for the combined sewer overflow (CSO) event in primary models that were used to evaluate the citywide effect of events on daily ED visits for GI illness. The variables are as specified in Equation 1b; however, we additionally assessed the effect of any event ≥67th percentile of volume and ≥85th percentile of volume in the 1 wk prior, 2 wk prior, or 3 wk prior in comparison with no event in that time frame. The effect estimates were compared to the primary results (large volume event defined as ≥75th percentile) to identify potential cut points indicating especially increased risk for GI infections.

To explore effect modification by area-level poverty and season, the main analyses were repeated with the addition of a product term. The models were specified as follows:

$$Log\,(ED_t) = \alpha + \beta_i \mathrm{CSO}_{ti} + \gamma_i precip_{ti} + \gamma_4 poverty_{ti} + \gamma_6 weekend_{ti} + \gamma_7 season_{ti} + \gamma_8 holiday_{ti} + \gamma_j hosp_{ti} + \delta_{1i} CSO_{ti} \times poverty_{ti} + ns(t, degrees\ of\ freedom = 4), \quad (1c)$$

$$Log\,(ED_t) = \alpha + \beta_i \mathrm{CSO}_{ti} + \gamma_i precip_{ti} + \gamma_4 warm_{ti} + \gamma_6 weekend_{ti} + \gamma_7 season_{ti} + \gamma_8 holiday_{ti} + \gamma_j hosp_{ti} + \delta_{1i} CSO_{ti} \times warm_{ti} + ns(t, degrees\ of\ freedom = 4), \quad (1d)$$

where all variables are as specified in Equation 1a, poverty is an indicator variable representing whether the patient's neighborhood was an area with high poverty, and *warm* represents whether the ED visit occurred in the warm season (May–September). To assess significance of the interaction, the likelihood ratio test statistic for the product term was assessed at an alpha of 0.1. Models that included dummy variables for CSO event volumes led to multiple product terms. For these models, evidence of significant interaction was evaluated using likelihood ratio chunk tests for multiple predictors. Weekly precipitation was included in each of these models.

We were particularly interested in examining the effectiveness of infrastructure improvements in preventing GI illness associated with CSO events. We therefore repeated the CSO–GI analyses with the inclusion of dummy variables representing infrastructure improvement periods. The before period was defined as 2002–2005, the during period was defined as 2006–2008, and the after period was defined as 2009–2013. All models controlled for the effects of precipitation. For CSO events of any volume within the previous 1-, 2- or 3-wk we modeled:

$$Log\,(ED_t) = \alpha + \beta_i \mathrm{CSO}_{ti} + \gamma_i precip_{ti} + \gamma_4 during_{ti} + \gamma_5 after_{ti} + \gamma_6 weekend_{ti} + \gamma_7 season_{ti} + \gamma_8 holiday_{ti} + \gamma_j hosp_{ti} + \delta_{1i} CSO_{ti} \times during_{ti} + \delta_{2i} CSO_{ti} \times after_{ti} + ns(t, degrees\ of\ freedom = 4), \quad (1e)$$

where all variables are as specified in Equation 1a. Evidence of significant interaction was evaluated using likelihood ratio chunk tests for multiple predictors. Period specific associations were

**Table 1.** Number of days with CSOs and average volume of effluent per day in Atlanta, 2002–2013.

| | Days with CSOs | | Total volume of effluent on days with events | |
|---|---|---|---|---|
| | *n* | Average per week | Average vol (kgals) | SD |
| Overall | 725 | 1.16 | 55,522 | 116,192 |
| Implementation period | | | | |
| Before (2002–2005) | 362 | 2.31 | 58,827 | 101,474 |
| During (2006–2008) | 236 | 1.51 | 30,071 | 43,804 |
| After (2009–20013) | 127 | 0.49 | 93,396 | 204,459 |
| Season | | | | |
| Winter | 176 | 1.26 | 52,561 | 72,754 |
| Spring | 168 | 1.20 | 61,548 | 105,726 |
| Summer | 258 | 1.84 | 48,286 | 144,227 |
| Fall | 123 | 0.98 | 66,705 | 113,441 |
| CSO volume categories[a] | | | | |
| High volume events[b] | 181 | 0.29 | 174,458 | 186,241 |
| Medium volume events[c] | 363 | 0.58 | 22,954 | 13,348 |
| Low volume events[d] | 181 | 0.29 | 1,901 | 1,866 |
| CSO outfall locations | | Proportion of events | | |
| Tanyard | 470 | 0.65 | 12,967 | 19,824 |
| Clear Creek | 431 | 0.59 | 17,900 | 27,171 |
| North | 435 | 0.60 | 9,885 | 16,814 |
| Greensferry | 308 | 0.42 | 6,207 | 12,738 |
| Custer | 210 | 0.29 | 19,192 | 27,984 |
| West | 70 | 0.10 | 140,205 | 243,083 |
| McDaniel | 149 | 0.21 | 11,482 | 14,986 |
| Intrenchment | 328 | 0.45 | 22,250 | 30,903 |

Note: A time-series plot of the data can be found in Figure 2. CSO, combined sewer overflow; SD, standard deviation.
[a]Categories based on total volume of discharge across all outfall locations.
[b]CSO event ≥75th percentile of volume (56,548 kgal) for CSO events in Atlanta, 2002–2013.
[c]CSO event 25th–74th percentile of volume for CSO events in Atlanta, 2002–2013.
[d]CSO event <25th percentile of volume (6,183 kgal) for CSO events in Atlanta, 2002–2013.

calculated by exponentiating the sum of $\beta_i$ and $\delta_{ni}$, where $n$ is the period of interest. Similarly, for volume-specific CSO events, we allowed for effect modification by infrastructure improvement period with the inclusion of product terms (Volume $Category_{ni} \times period_{ni}$).

### *Precipitation–GI Illness Models and Submodels*

Because CSOs have been shown to potentiate sewage contamination in surface water following precipitation events, creating greater potential for human health impacts via increased pathogen load, we hypothesized that the reduction of CSOs in the city of Atlanta would lead to a reduction in risk of GI illness following heavy rainfall events.[11–18] Therefore, we were interested in understanding the effect of rainfall on GI illness independent of CSO events and investigating whether this relationship differed as improvements were made to the sewerage system. First, we assessed the effect of precipitation on ED visits for GI across the entire study period. The model was specified as:

$$Log\,(ED_t) = \alpha + \beta_i precip\_90_{ti} + \gamma_1 weekend_{ti} + \gamma_2 season_{ti} + \gamma_3 holiday_{ti} + \gamma_j hosp_{ti} + ns(t, degrees\ of\ freedom = 4) \tag{2}$$

Our exposure ($precip\_90_{ti}$ was defined as weekly cumulative sum of precipitation above the 90th percentile to capture the impact of heavy precipitation, which has been linked to GI illness in prior epidemiological studies[5,7,8] and may have a greater influence on CSO events than less extreme precipitation events.[10,11] All other variables are as specified in Equation 1a. As in the CSO–GI models, we allowed for effect modification by infrastructure improvement period with the inclusion of product terms ($\text{Precip\_90}_{ni} \times \text{period}_{ni}$).

## Results

### *Descriptive Statistics*

Data on CSO events in the city of Atlanta were available for all but five quarters (459 d) across the 4,366-d study period (2002–2013). The quarters where we were unable to obtain records of CSO events occur throughout the study period and included quarter 4 of 2002, quarter 2 of 2005, quarter 4 of 2008, and quarters 3 and 4 of 2012. These periods are coded as missing in the analysis. During the 12-y study period, the city of Atlanta reported 725 CSO events across seven outfall locations, where an event is defined as a day with any discharge reported from at least one outfall location. There was an average of 1.16 events per week and an average total effluent per event of 55,522 kgals (Table 1). These events were spread disproportionately throughout the year and study period. When broken down by season, the highest average number of events occurred in the summer (1.84 events/wk), followed by the winter (1.26 events/wk), spring (1.20 events/wk), and fall (0.98 events/wk). Conversely, the average volume of effluent per event was highest in the fall, followed by the spring, winter, and summer. The average number of events per week decreased across the study period. This pattern is highlightedin Figure 2. In the period before infrastructure improvements, Atlanta averaged 2.31 events/wk, followed by 1.51 events/wk in the period during improvements, and 0.49 events/wk in the period after improvements (Table 1). The average volume of effluent per event did not follow this same pattern, however. The highest average volume of effluent per event was observed in the period after improvements, and the lowest was observed in the period during improvements (93,396 kgals per event vs. 30,071 kgals per event; Table 1).

Across the entire study period, large volume events (total discharge ≥75 th percentile of volume) had an average volume of effluent of 174,458 kgals in comparison with medium volume events (total discharge between 25th and 74th percentile of volume) with average discharge of 22,954 kgals and small volume

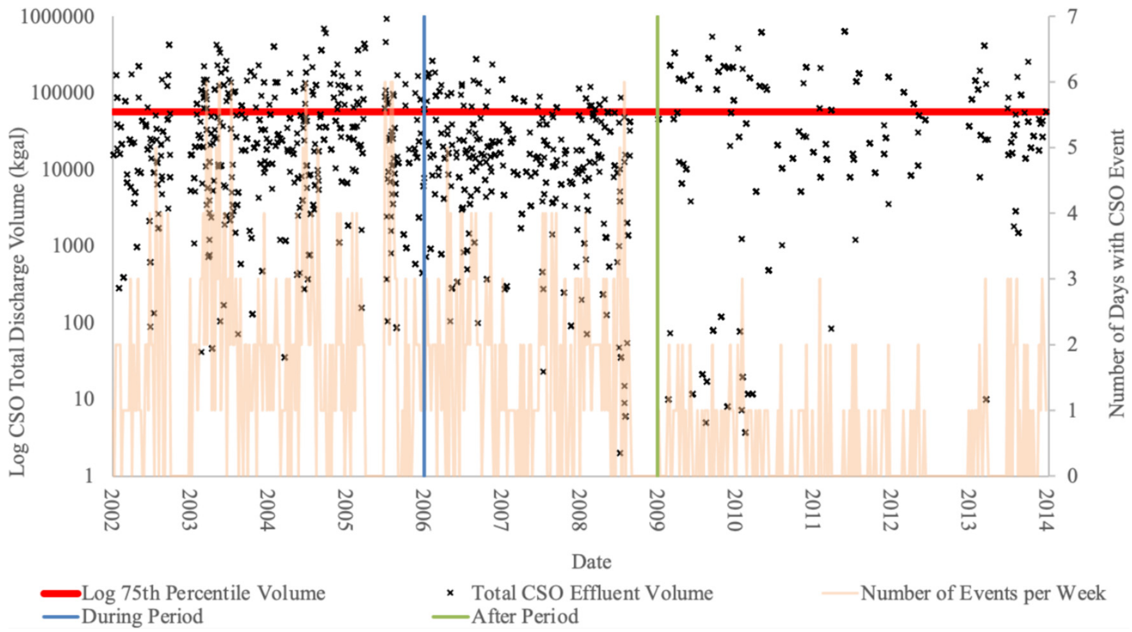


**Figure 2.** Time-series plot of combined sewer overflow (CSO discharges by volume (kgals) and number within a week, 2002–2013. Event volumes are plotted on a logarithmic scale, with the thick horizontal line indicating discharges above the large event threshold. The number of days with an event at any outfall location within a given week are plotted on a secondary axis. All events prior to 2006 fall in the period before infrastructure improvements, denoted by the vertical line on the left. Events in 2009 and later fall in the period after infrastructure improvements, as indicated by the vertical line on the right. Summary data can be found in Table 1. Note: CSO, combined sewer overflow.

events (total discharge <25 th percentile of volume) with average discharge of 1,901 kgals (Table 1). Figure 2 shows the total number of events and daily volume of CSO effluent per day across the study period, highlighting events above various large volume event cut points used in the main epidemiological analysis and sensitivity analyses.

Frequency and volume of discharges varied across sites (Table 1). The number of discharges ranged from 70 to 470, contributing to 10%–65% of the CSO events. Average volume of discharges was highest at the West Area facility (140,205 kgals); however, this location experienced the fewest overflows. On average, discharges were smallest at the Greensferry site (6,207 kgals). We also examined the distribution of discharges at each site on days with large, medium, and small volume events (Table S1). The average volume of discharge at each site was greatest for days with large volume events, followed by days with medium and small volume events, respectively. This finding indicates that large discharges triggered large volume events.

Because CSO events are most often triggered by heavy precipitation, we explored the distribution of CSO events following various categories of precipitation in the week immediately preceding events (Figure 3; Table S2). There is a clear trend showing that as precipitation in the preceding week increased, the number and volume of CSO events also increased. A total of 15.51% (476 d) of days with no CSO event occurred after a week with no precipitation in comparison with 2.26% (11 d) of days with CSO events. Comparatively, the percentage of days [60.64% (107 d)] with large volume events fell after weeks where the sum of precipitation was ≥75th percentile, followed by 31.01% (111 d) of days with medium volume events, 24.02% (43 d) of days with small volume events, and 22.04% (676 d) of days with no CSO

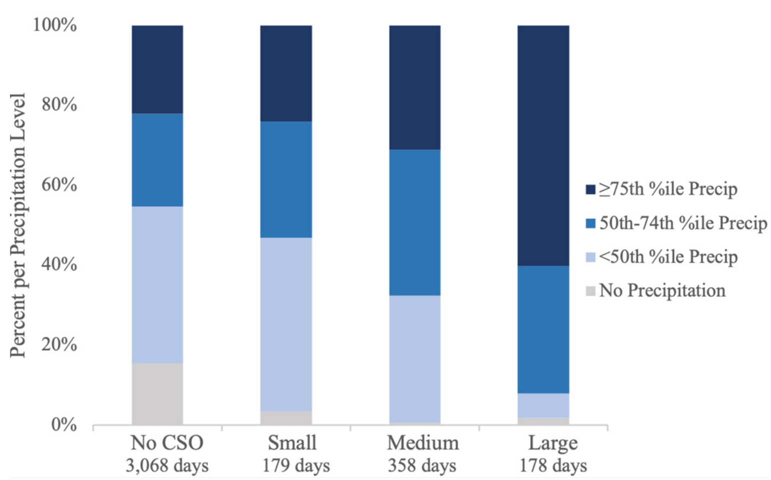


**Figure 3.** Percent of combined sewer overflow (CSO) events following various levels of weeklong precipitation. Events <25th percentile of volume (6,183 kgal) are defined as small volume, events 25th–74th percentile of volume are defined as medium volume, and events ≥75 th percentile of volume (56,548 kgal) are defined as large volume. Precipitation data collected at Hartsfield Jackson Airport, Atlanta, Georgia, 2002–2013. Summary data are found in Table S2.

**Table 2.** Average number of ED visits for GI illness among residents of City of Atlanta ZIP codes, 2002–2013.

| | ED visits for GI infections ($n = 22{,}079$) | |
|---|---|---|
| | Total ED visits | Mean per day (SD) |
| Overall | 22,079 | 5.05 (3.54) |
| Season | | |
| Winter | 6,472 | 6.07 (4.12) |
| Spring | 6,175 | 5.59 (3.79) |
| Summer | 4,414 | 4.00 (2.69) |
| Fall | 5,018 | 4.60 (3.00) |
| ZCTA poverty (%)[a] | | |
| High[b] ($n = 1{,}809{,}411$) | 13,408 | 3.07 (2.62) |
| Low[c] ($n = 391{,}424$) | 8,631 | 1.98 (1.67) |

Note: ED, emergency department; GI, gastrointestinal; SD, standard deviation; ZCTA, ZIP Code Tabulation Areas.
[a]ZCTA used to represent U.S. Postal Service ZIP Codes.
[b]ZCTA percent poverty equal to or greater than the median (14.7%) for Atlanta. from the American Community Survey 2007–2011.
[c]ZTCA percent poverty less than the median (14.7%) for Atlanta, from the American Community Survey 2007–2011.

event. Events in dry conditions may be due to backups caused by grease, fallen leaves, or other debris in the sewerage system.[32] A time-series plot of weekly sum of precipitation alongside weeks with various levels of CSO events is shown in Figure S1.

A total of 22,079 ED visits occurred for GI illness among patients visiting metropolitan Atlanta hospitals whose billing ZIP code encompassed City of Atlanta property; this equates to an average of 5.05 visits per day across the study period (Table 2). The average number of visits per day was highest in the winter (6.07 visits/d), followed by the spring (5.59 visits/d), fall (4.60 visits/d), and summer (4.00 visits/d). The daily time-series plot of ED visits for GI illness shows that the number of cases tended to peak in the winter months and that the percentage of all ED visits attributed to GI illness increased across the study period (Figure 4).

Across Atlanta ZCTAs, the percentage of residents living in poverty during 2007–2011 ranged from 2.2% to 35.6% (median = 14.7%). The median value was used to categorize ZCTAs into high poverty areas (ZCTAs with >14.7% of residents living in poverty) and low poverty areas (ZCTAs with ≤14.7% of resident living in poverty) (Figure 1). Areas with high poverty had a population of 1,809,411 and contributed an average of 3.07 ED visits for GI illness per day across the study period (4,366 d), whereas areas with low poverty had a combined population of 391,424 and contributed an average of 1.98 visits per day (Table 2).

### *Characterization of CSO–GI Illness Associations across the Study Period*

Table 3 presents associations between ED visits for GI illness and CSO events 1–3 wk prior, and Figure 5 presents associations for events 1 wk prior. There was no association between any CSO event in the prior week and ED visits for GI illness in comparison with prior weeks with no CSO events. However, occurrence of a large volume CSO event in the prior week was associated with an increase in ED visits for GI illness in comparison with no event, in both models with and without adjustment for precipitation [adjusted for precipitation, RR = 1.09; 95% confidence interval (CI): 1.03, 1.14)]. Occurrence of a medium volume event or a small volume event in the prior week was not associated with an increase in ED visits for GI illness. Across all CSO exposure definitions, we found no association with GI illness for events 2 wk prior or 3 wk prior to the visit. In general, adjusting for precipitation led to stronger estimates of the association; however, the parameter estimate related to weekly precipitation was significant only in models of the prior week where CSO events were stratified by volume.

Results from a sensitivity analysis in which exposure volume categories were varied did not provide evidence of more robust associations (see Table S3). When CSO events were categorized by volume tertiles, the association between events ≥67th percentile and ED visits for GI illness was weakened in comparison with high volume events defined as upper quartile; nevertheless, when adjusting for precipitation, there was still a significant association

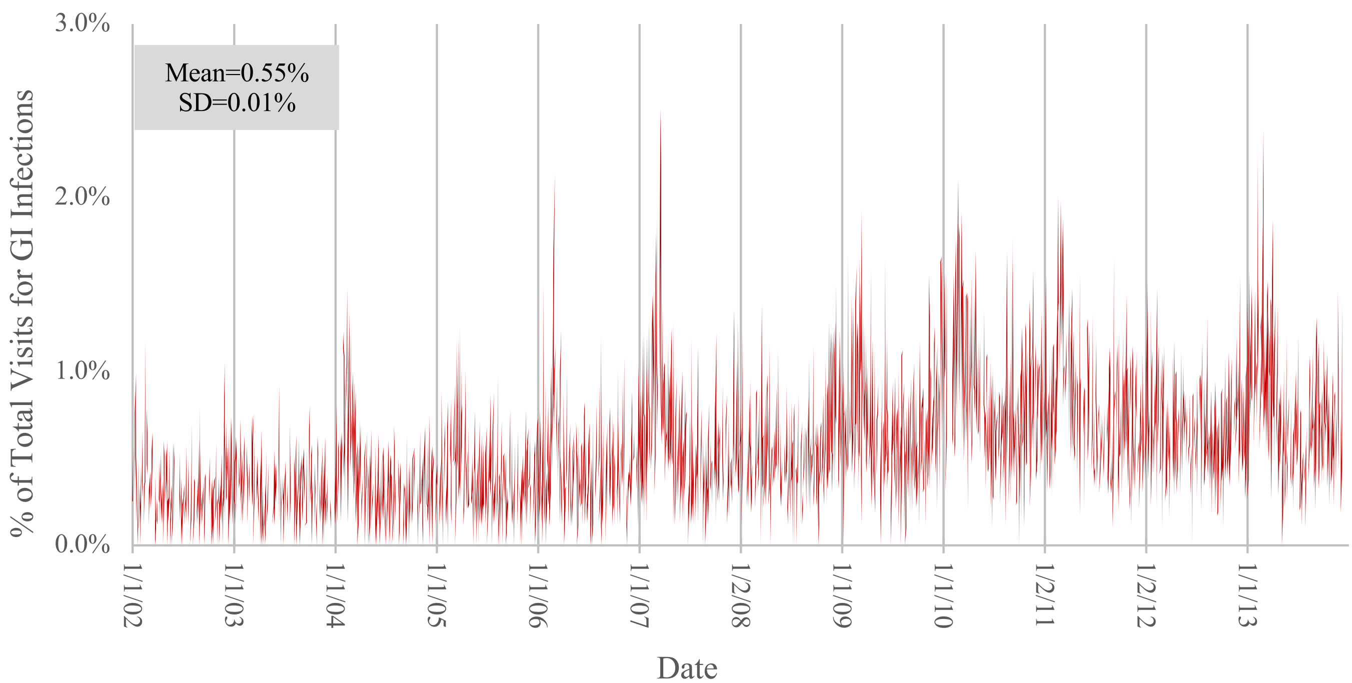


**Figure 4.** Time-series plot of daily ED visits for GI illness, Atlanta, Georgia, 2002–2013. The plot is normalized to the total number of ED visits at participating metropolitan Atlanta hospitals to account for changes across the study period in the number of hospitals contributing to the study, changes in population, and overall ED usage. Note: ED, emergency department; GI, gastrointestinal.

**Table 3.** Estimated rate ratios and 95% CI for the effect of CSO events within a given week on daily count of ED visits for GI illness in Atlanta, 2002–2013.

| | 1 Wk prior | | 2 Wk prior | | 3 Wk prior | |
|---|---|---|---|---|---|---|
| | RR (95% CI) | *p*-Value | RR (95% CI) | *p*-Value | RR (95% CI) | *p*-Value |
| Model with CSO as dichotomous variable | | | | | | |
| Any event[a] vs. no event | | | | | | |
| Unadjusted for precipitation[b] | 1.01 (0.97,1.05) | 0.55 | 1.01 (0.97, 1.05) | 0.52 | 1.02 (0.98, 1.06) | 0.32 |
| Adjusted for precipitation[c] | 1.03 (0.98, 1.07) | 0.24 | 1.03 (0.98, 1.07) | 0.22 | 1.02 (0.98, 1.06) | 0.39 |
| Model with CSO defined by volume, 4-level variable | | | | | | |
| Large volume event[d] vs. no event | | | | | | |
| Unadjusted for precipitation | 1.05 (1.01, 1.09) | 0.03 | 1.01 (0.97, 1.05) | 0.78 | 1.03 (0.99, 1.07) | 0.20 |
| Adjusted for precipitation | 1.09 (1.03, 1.14) | <0.01 | 1.03 (0.98, 1.08) | 0.32 | 1.03 (0.98, 1.09) | 0.19 |
| Medium volume event[e] vs. no event | | | | | | |
| Unadjusted for precipitation | 0.99 (0.95, 1.03) | 0.73 | 0.99 (0.96, 1.03) | 0.77 | 1.00 (0.96, 1.04) | 0.86 |
| Adjusted for precipitation | 0.99 (0.96, 1.03) | 0.64 | 1.00 (0.96, 1.04) | 0.97 | 1.01 (0.96, 1.05) | 0.80 |
| Small volume event[f] vs. no event | | | | | | |
| Unadjusted for precipitation | 0.97 (0.92, 1.01) | 0.13 | 1.02 (0.98, 1.07) | 0.30 | 1.00 (0.96, 1.05) | 0.96 |
| Adjusted for precipitation | 0.98 (0.93, 1.02) | 0.28 | 1.03 (0.98, 1.08) | 0.22 | 1.00 (0.96, 1.05) | 0.88 |

Note: All analyses conducted using Poisson generalized linear models with the inclusion of covariates to adjust for time trends, hospital participation. Graphical representation of the data can be found in Figure 5. CI, confidence interval; CSO, combined sewer overflow; ED, emergency department; GI, gastrointestinal; RR, rate ratios; Wk, week(s).
[a]CSO event of any volume.
[b]Sum of precipitation within the specified week not included in model.
[c]Sum of precipitation within the specified week included in model.
[d]CSO event ≥75th percentile of volume (56,548 kgal) for CSO events in Atlanta, 2002–2013.
[e]CSO event 25th–74th percentile of volume for CSO events in Atlanta, 2002–2013.
[f]CSO event <25th percentile of volume (6,183 kgal) for CSO events in Atlanta, 2002–2013.

between ED visits for GI illness and occurrence of an event ≥67th percentile in the prior week in comparison with no event (RR = 1.05; 95% CI: 1.00, 1.11). As in the pattern from the primary analyses, we found no significant associations for lower tertile events in the prior week or CSO events of any size occurring outside of the 1-wk time frame. When CSO events were categorized as large for volumes ≥85th percentile, we observed a significant association comparing events ≥85th percentile in the past week to no event when adjusting for precipitation (RR = 1.06; 95% CI: 1.01, 1.03). An interesting finding was that the stricter cutoff for large volume events (85th percentile) also showed an attenuated risk when compared with large volume events in the primary analysis (upper quartile events).

Figure 6 and Table S4 present associations between ED visits for GI illness and occurrence of a CSO event (in comparison with no event and adjusted for all covariates), allowing for effect modification by ZCTA-level poverty. At an alpha of 0.1, there was evidence of significant interaction by poverty in all models except the model with "any event" as the exposure at a 1-wk lag ($p = 0.15$). The resulting *p*-values from the remaining 5 models ranged from <0.0001 to 0.06. In general, the effect of CSO events on ED visits was higher in areas with low poverty. Among low poverty areas, there was a 12% increase in the number of ED visits for GI illness when there was a large volume CSOs in the prior week (RR = 1.12; 95% CI: 1.05, 1.20). Among high poverty areas, the CSO effect was weaker than that in low poverty areas, but still significant (RR = 1.06; 95% CI: 1.00, 1.13). Medium volume and small volume events in the prior week had no significant effect on ED visits for GI illness among high or low poverty areas. Among low poverty areas, ED visits for GI illness were associated with the occurrence of any CSO event (RR = 1.08; 95% CI: 1.02, 1.14), a large volume event (RR = 1.12, 95% CI: 1.05, 1.20), and a medium volume event (RR = 1.06; 95% CI = 1.00, 1.12) 2 wk prior. There was no association between CSO events 2 wk prior and GI illness among areas with high poverty. Finally, there was an association between ED visits for GI illness and any CSO event 3 wk earlier (RR = 1.07; 95% CI: 1.01, 1.14) as well as medium volume events 3 wk earlier (RR = 1.07; 95% CI: 1.01, 1.13) within low poverty areas; we found no such associations within high poverty areas. Results from an analysis of effect modification by season may add additional context to our findings related to poverty and exposure pathways (Table S5). An analysis of potential effect modification by season (warm vs. cool) produced

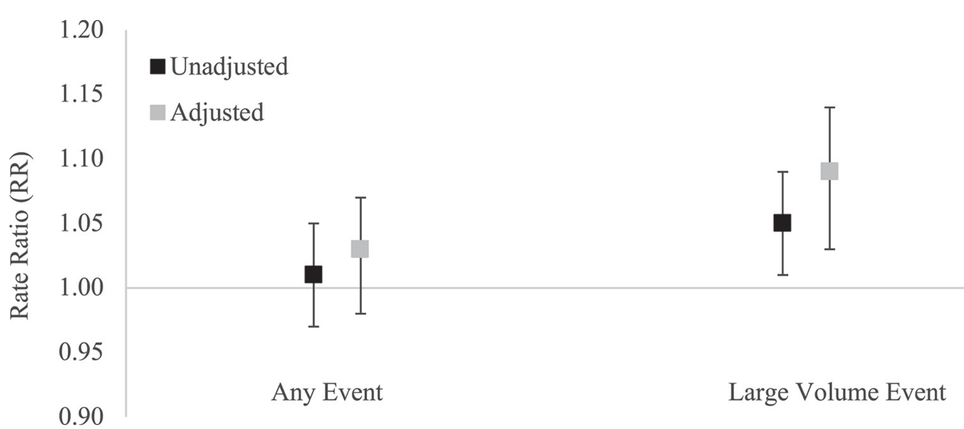


**Figure 5.** Comparison of rate ratios (RRs) and 95% confidence intervals for the association between ED visits for GI illness and CSO events of various volumes in the prior week, adjusted and unadjusted for weekly sum of precipitation, Atlanta, Georgia, 2002–2013. Comparison group for all models is no event in the prior week. Any is a CSO event of any volume. Large volume events are defined as an event ≥75 th percentile of volume for CSO events in Atlanta during the study period. Summary data can be found in Table 3. Note: CSO, combined sewer overflow; ED, emergency department; GI, gastrointestinal.

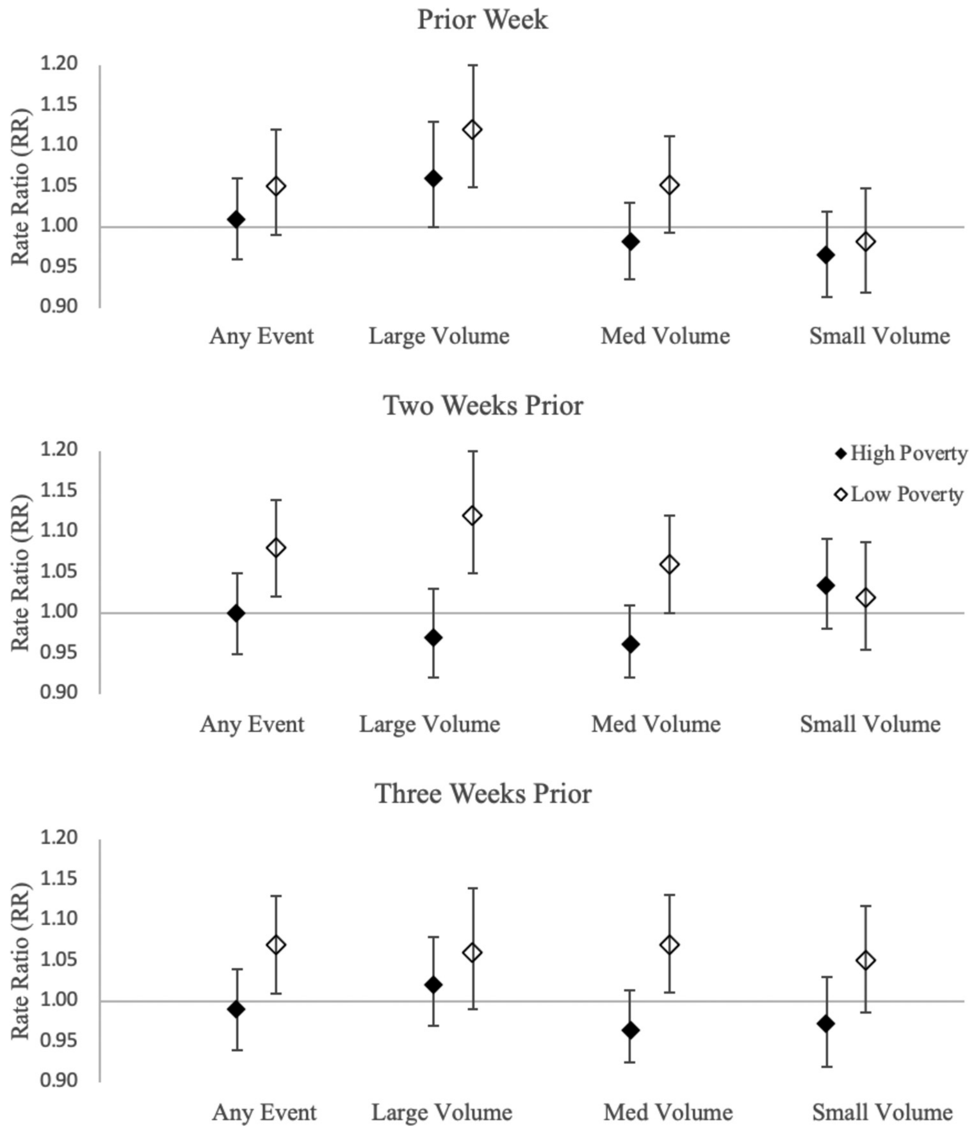


**Figure 6.** Comparison of rate ratios (RRs) and 95% confidence intervals for the association between ED visits for GI illness and CSO events of various volumes of effluent in the specified week allowing for effect modification by area-level poverty, Atlanta, Georgia, 2002–2013. All estimates adjusted for weekly sum of precipitation, time trends and hospital participation. Any is a CSO event of any volume. Large volume events are defined as an event ≥75 th percentile of volume. "Med" volume events are defined as an event 25th–74th percentile of volume, and small volume events are defined as an event <25 th percentile of volume. No event in the specified week (no) is the comparison group for all models. See Table S4 for numerical presentation of results. Note: CSO, combined sewer overflow; ED, emergency department; GI, gastrointestinal; Med, medium.

mixed results. For five out of six models, we found no evidence of effect modification by season in the CSO–GI association (Table S5). Nonetheless, estimated warm season risk tended to be higher than risk in the cool season, although this pattern was not consistent across all models.

### *Characterization of CSO–GI Illness and Precipitation–GI Infection Associations across Infrastructure Improvement Periods*

Results from our analysis of effect modification by infrastructure improvement period on the CSO–GI associations are presented in Table 4. At an alpha of 0.1, we found evidence of significant interaction by period in only the model comparing any event to no event in the prior week. For this model, within the period before improvements, we estimated a 14% decrease in ED visits for GI illness following weeks with a CSO event in comparison with weeks without events. We did not identify evidence of significant associations in either the periods during or after improvements or at longer lags.

Large volume CSO events in the week prior were associated with an increase in ED visits for GI illness in comparison with weeks with no event in the periods during (RR = 1.13; 95% CI: 1.04, 1.22) and after (RR = 1.09; 95% CI: 1.02–1.17) improvements but not in the period before. Conversely, at a 2-wk lag, only large volume events in the period before improvements were associated with an increase in ED visits for GI illness (RR = 1.16; 95% CI: 1.05, 1.28). There was no association between large volume CSOs 3 wk prior and ED visits for GI illness within any period.

Across the entire study period, weeks with heavy precipitation (above the 90th percentile) were associated with a decrease in ED visits for GI infections in comparison with weeks with no precipitation at a 1-wk lag (RR = 0.93; 95% CI: 0.87, 0.99; Table 5). We did not identify evidence of significant interaction by infrastructure

**Table 4.** Estimated rate ratios and 95% CI for the effect of CSO events within a given week on daily count of ED visits for GI illness in Atlanta, 2002–2013, allowing for effect modification by infrastructure improvement period.

| | 1 Wk prior | | 2 Wk prior | | 3 Wk prior | |
|---|---|---|---|---|---|---|
| | RR (95% CI) | *p*-Value | RR (95% CI) | *p*-Value | RR (95% CI) | *p*-Value |
| Any event[a] | — | 0.01 | — | 0.32 | — | 0.17 |
| Before[b] | 0.86 (0.77, 0.98) | — | 1.09 (0.96, 1.25) | — | 1.05 (0.92, 1.20) | — |
| During[c] | 1.04 (0.96, 1.12) | — | 0.98 (0.91, 1.07) | — | 1.08 (1.00, 1.17) | — |
| After[d] | 1.05 (1.00, 1.11) | — | 1.04 (0.98, 1.09) | — | 0.99 (0.94, 1.05) | — |
| Large event[e] | — | 0.18 | — | 0.05 | — | 0.42 |
| Before | 1.00 (0.91, 1.11) | — | 1.16 (1.05, 1.28) | — | 1.08 (0.98, 1.20) | — |
| During | 1.13 (1.04, 1.22) | — | 0.99 (0.91, 1.07) | — | 1.05 (0.97, 1.14) | — |
| After | 1.09 (1.02, 1.17) | — | 1.02 (0.96, 1.08) | — | 1.01 (0.95, 1.07) | — |

Note: All analyses conducted using Poisson generalized linear models with the inclusion of covariates to adjust for precipitation, time trends, hospital participation; reference group no event. —, no data; CI, confidence interval; CSO, combined sewer overflow; ED, emergency department; GI, gastrointestinal; RR, rate ratios; Wk, week(s).
[a]CSO event of any volume.
[b]Period prior to major improvements in stormwater infrastructure (2002–2005).
[c]Period in which major stormwater infrastructure projects take place (2006–2008).
[d]Period following major stormwater infrastructure projects (2009–2013).
[e]CSO event ≥75th percentile of volume (56,548 kgal) for CSO events in Atlanta, 2002–2013.

improvement period and observed no clear trend in the precipitation–GI association across the periods before, during, and after improvements.

## Discussion

We found that large volume CSO events were associated with an increased risk of ED visits for GI illness in Atlanta, independent of precipitation, with variation in strength of this effect by various covariates examined. For the population as a whole, we observed a 9% (95% CI: 3%, 14%) increase in ED visits following a week with at least one large volume event. For events in the prior 2- or 3-wk periods, we observed a tendency for increased ED visits, but this result was not statistically significant.

Infrastructure improvement projects were successful in decreasing the number of events during the study period from 2.31 events per week in the period before improvements to 0.49 events per week in the period after improvements. Although the total number of events decreased, the volume of effluent per event remained unchanged. Results from our analysis of the impact of infrastructure projects on reducing rates of ED visits for GI illness did not provide evidence of a protective effect of infrastructure improvements for precipitation or CSO related risks. Although the relative risk was not reduced, because an overall reduction in CSO events occurred, we believe it is possible that the absolute number of ED visits for GI illness attributable to CSO events had decreased over the study period.

Several biological and environmental pathways may contribute to the observed findings. Because higher volume CSO events discharge a greater magnitude of untreated sewage, they may increase the total load of pathogens in surface water past an acceptable threshold,[11,12] Medium and small volume discharges, on the other hand, may not release enough sewage to consistently reach this threshold. This could contribute to why we observe a population-wide effect following large, but not small or medium, volume events.

A variety of pathogenic microorganisms that cause enteric disease may be found in untreated sewage.[11,16] These pathogens have a diverse set of incubation and symptomatic periods. For example, symptoms of cryptosporidiosis typically begin 2 to 10 d following exposure and can last up to 4 wk.[31] Comparatively, norovirus symptoms begin within 2 d of exposure and tend to subside within 3 d.[33] This variation in time of first onset of symptoms and symptom duration could contribute to the variable timing in visits to the ED (from 1 to 3 wk after CSO events).

An interesting aspect is that, our initial hypothesis that the CSO–GI association would be stronger in high poverty areas was not supported by this analysis. Instead, our findings suggest that the association is stronger among areas with lower poverty. In lower poverty neighborhoods, we observed a 12% increase in ED visits (95% CI: 5%, 20%). Among areas with high poverty, however, the pattern of risk following CSO events was similar to the study population as a whole. Furthermore, among areas with low poverty, we also observed increased risk for GI illness 2 and 3 wk after a CSO event. Our findings indicate that these areas are also more sensitive to volume of effluent; in addition to large volume events, we observed significant positive associations following medium volume events among low poverty areas. The potential for exposure to occur through multiple routes, including drinking water or recreation, could contribute to the excess risk in areas with low poverty. Studies have shown a positive relationship between SES and leisure time physical activity.[34] In Atlanta, this may mean high SES individuals have more access to recreational opportunities on the Chattahoochee River, for example. Therefore,

**Table 5.** Estimated rate ratios and 95% CI for the effect of cumulative weekly precipitation 90th percentile and above within a given week on daily count of ED visits for GI illness in Atlanta, 2002–2013, allowing for effect modification by infrastructure improvement period.

| | 1 Wk prior | | 2 Wk prior | | 3 Wk prior | |
|---|---|---|---|---|---|---|
| | RR (95% CI) | *p*-Value | RR (95% CI) | *p*-Value | RR (95% CI) | *p*-Value |
| Overall | 0.93 (0.87, 0.99) | 0.03 | 0.97 (0.9, 1.04) | 0.41 | 1.03 (0.97, 1.10) | 0.33 |
| Infrastructure improvement period | — | 0.46 | — | 0.23 | — | 0.75 |
| Before[a] | 0.83 (0.68, 1.02) | — | 1.13 (0.92, 1.38) | — | 0.97 (0.79, 1.20) | — |
| During[b] | 0.97 (0.85, 1.11) | — | 1.00 (0.88, 1.15) | — | 1.06 (0.93, 1.22) | — |
| After[c] | 0.93 (0.85, 1.00) | — | 0.94 (0.87, 1.02) | — | 1.01 (0.94, 1.10) | — |

Note: All analyses conducted using Poisson generalized linear models with the inclusion of covariates to adjust for precipitation, time trends, hospital participation; reference group no precipitation. —, no data; CI, confidence interval; CSO, combined sewer overflow; ED, emergency department; GI, gastrointestinal; RR, rate ratios; Wk, week(s).
[a]Period prior to major improvements in stormwater infrastructure (2002–2005).
[b]Period in which major stormwater infrastructure projects take place (2006–2008).
[c]Period following major stormwater infrastructure projects (2009–2013).

these individuals could have greater exposure via recreational pathways in contrast with low SES individuals, who may predominantly be exposed through the municipal drinking water system, which may perpetuate a lower relative risk in this setting. The lower exposure via municipal drinking water is because the water intake points for the city of Atlanta primarily lie upstream of the CSO outfalls in question, and water treatment systems are generally well equipped to remove enteric pathogens.[23] Nonetheless, there may be CSS feeding directly into surface reservoirs in surrounding municipalities that could influence contaminant levels in Atlanta drinking water, as well as intrusion in the drinking-water distribution system downstream of the treatment plant.[5] This factor is unaccounted for in the current study.

Although our findings indicate a stronger association between CSO events and GI illness for areas with low poverty, it is important to note that a disproportionate number of ED visits for GI illness come from areas with a high percentage of residents living in poverty ($n = 13{,}408$ vs. $n = 8{,}631$). Thus, even though the estimated effect in areas with high poverty is smaller than among areas with low poverty, a greater share of individuals visiting the ED following CSO events may be from areas with high poverty because our models estimate relative, and not absolute, risks. There are a variety of challenges related to neighborhood-level SES that may contribute to the disproportionate number of ED visits for GI illness from areas where a high percentage of individuals live in poverty. These underlying challenges include increased rates of obesity and chronic disease that may increase severity of GI illness, availability of health insurance, and access to primary care.[35] These factors may affect health-seeking behavior. For example, people living in higher poverty areas may have a higher threshold of illness before they seek care for GI symptoms due to lack of insurance access and cost of care.[35] Because of this, it is possible that we are observing disproportionate underreporting from areas with high poverty.

Results from a sensitivity analysis where cut points for CSO event volume categories were varied provided mixed results. Although a relaxed cut point for large volume events resulted in an attenuated risk for ED visits for GI illness, a stricter cut point also produced an attenuated effect estimate. This result suggests that there is not a linear dose–response relationship between volume of event and risk of GI illness. One possible explanation for this finding is that for very large volume CSOs, the concentration of pathogens in the discharge is diluted. Although our study does not differentiate between multiple small or medium discharges and one large discharge, it is likely that large events are indicative of large discharges (Table S1). Prior studies of the effect of precipitation on GI illness support this explanation, termed the 'Concentration-Dilution Hypothesis" in the relevant literature, where heavy precipitation events initially flush out pathogens but then dilute their concentration in a water source as the event progresses.[6,36] In general, however, additional evidence from our study (i.e., greater risk for GI illness following large volume events in comparison with medium and small volume events) supports the notion that volume of CSO effluent is positively correlated with risk.

To better understand the relative importance of recreational and drinking water exposures, we assessed whether the effect of CSOs was modified by season (warm vs. cool) (Table S5). The results of this analysis were largely inconclusive. We did not identify evidence of an interaction effect by season. One possible explanation for this is that recreational exposures through water-based activities, which are more popular in the warm season, are not the primary route of exposure. Nonetheless, the CSO–GI association tended to be stronger in warmer months, which could suggest that recreation is in fact an important pathway. Additional research is needed to clarify CSO exposure mechanisms.

Monitoring efforts by government and nonprofit organizations like the Chattahoochee Riverkeeper have provided a robust understanding of water quality in the Chattahoochee River as stormwater infrastructure improvements have progressed.[20,37] Overall, water quality in the area has improved with the updates: There has been an 80% reduction in levels of bacteria in the Chattahoochee since the early 1990s.[20] Given the improvements in water quality, our objective was to investigate the impact of stormwater infrastructure improvement on human health. Contrary to our initial hypothesis, we did not observe a diminished association between CSO events and ED visits for GI symptoms as a result of these projects. Because work was ongoing throughout the study period, it was not possible to establish strict definitions for infrastructure improvement periods. The lack of strict definitions may have limited our ability to estimate the true effect of infrastructure improvements. Nonetheless, we did observe a decrease in the average number of events per week as the infrastructure improvements progressed, suggesting that that absolute number of illnesses attributable to CSO events reduced over time.

A limited number of studies have examined the role of CSO events in GI illness; nevertheless, results from previous analyses are consistent with our findings. In Milwaukee, Redman et al. found a 50% increase in pediatric ED visits for diarrheal illness 3–7 d after high volume CSO events among people who lived in areas that used Lake Michigan drinking water sources.[22] Similarly, Brokamp et al. identified a 16% increase in pediatric GI-related visits 2 d after CSO events in Cincinnati for children living within 500 m of an outfall site.[21] Although these studies support our findings of a temporal association between CSO events and ED visits for GI illness, there are some key distinctions. First, neither analysis explored a lagged effect past 1 wk; our study identified significant effects as far as 3 wk out for low poverty areas. Second, both studies were restricted to the pediatric population, which may contribute to the higher estimated risk from their analyses. Children are more susceptible to enteric agents because their immune systems are not fully developed,[38] and they may be more likely to be seen in the ED after the development of disease.[39] Finally, our study examined the population-level effect, rather than restricting to areas deemed vulnerable *a priori*, which may also contribute to the higher observed risk in the aforementioned studies.

Further support for the observed association between CSO events and GI illness comes from a spatial analysis in Massachusetts where the authors found that presence of CSOs modified the effect of heavy rainfall events.[5] Areas with CSOs discharging to drinking-water sources experienced an increase in ED visits for GI infections in the 8-d period following extreme precipitation, but in areas with CSOs discharging to recreational water bodies or without combined sewer systems there was no association.[5] These results contrast our findings related to heavy precipitation, though there were key distinctions between the two studies. First, we observed a protective effect of heavy precipitation when considered across the entire study period. Additionally, we did not consider direct modifications by CSOs, and instead we assessed the association as updates to infrastructure were implemented. Nonetheless, we found no significant difference in the rate of ED visits for GI illness following heavy precipitation events across the infrastructure improvement periods.

The use of ED visits for GI infections as an indicator for overall GI illness is a limitation of this study. Although this practice is commonly used in epidemiological studies, only a small percentage of individuals with GI symptoms visit the ED, and these patients may not be representative of all cases.[5] This factor may be of particular importance for our investigation of effect modification by neighborhood-level poverty because SES may influence if and where an individual seeks care. Because the hospital records did not provide individual-level data, ZCTA-level poverty was used as a proxy for individual indicators of SES; however, some studies have demonstrated that when an aggregated variable is expressed as a proportion and defined by internal cut points, as in our study, we can expect the impact of the bias to be null.[40] Ideally precipitation would be measured at each outfall location, but these data were not available for this analysis. Instead, the use of a single precipitation measurement at Atlanta Hartsfield Jackson Airport introduces spatial incompatibility between study population and collected rainfall data. This measurement error would tend to bias the estimated effect of rainfall on GI illness toward the null.[41] Although prior studies of the role of CSOs in GI illness have shown that distance from residence to outfall is an important factor in risk, we were unable to include residential proximity in our analysis due to small numbers of cases from individual ZIP codes.[5,21,22] In Atlanta, however, the CSO outfalls are located primarily in neighborhoods with high poverty, where we observed relatively lower risk of GI illness in the weeks following a CSO event. This indicates that factors other than residential proximity may be important in the development of illness due to CSOs.

Because multiple comparisons were made for a single dependent variable (daily ED visits for GI infections), the probability of observing a spurious significant result is increased in our study. To assess the implications to this, we can consider the level of significance using the Bonferroni method as follows:

$$\alpha = 0.05/k, \tag{3}$$

where $k$ is the number of independent tests. We determined $k = 22$, combining models at multiple lags or types of precipitation control because we would expect these tests to be highly correlated. This results in a corrected $\alpha = 0.002$. When applied to our results, only high-volume events at 1- and 2-wk lags among low poverty areas would be considered significant. Nonetheless, it is important to consider trends and patterns in the results and not rely only on measures of statistical significance. When considered from this perspective, we found the rate of ED visits following a week with a CSO tended to be higher than instances without a CSO across multiple contexts.

There are a variety of strengths associated with the design of the current study. First, we were able to access detailed data describing CSO events in Atlanta. This access to detailed data enabled us to establish temporality between occurrence of CSO events and ED visits for GI illness. Additionally, the exposure data included measures of volume that supported an investigation into potential dose–response relationships between size of event and GI illness. Because the study period extended across 11 y, we were able to minimize bias due to long-term temporal trends within the analyses. Finally, because we were able to access ED visit data for the majority of Atlanta metropolitan hospitals, we could estimate population-level effects in addition to stratifying by neighborhood-level SES.

In conclusion, our findings, taken into context with those from previous studies, suggest that occurrence of high volume CSO events may increase risk for GI illness. This effect was stronger (on a relative scale) in Atlanta in neighborhoods with low levels of poverty in comparison with areas with high levels of poverty. Given the consistent, positive associations following high volume CSO events, as well as previous studies finding higher concentrations of contaminants in streams following rainfall events, avoiding exposure to surface water in the weeks following large rainfall events should be promoted to reduce the risk of GI illness.[11,42] Additionally, in the interest of public health, nationwide efforts to phase out CSS should continue to be prioritized.

## References


1. Lall U, Johnson T, Colohan P, Aghakouchak A, Brown C, McCabe G, et al. 2018. Chapter 3: Water. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, vol 2*. Reidmiller DR, Avery CW, Easterling DR, Kunkel KE, Lewis KLM, Maycock TK, eds. https://nca2018.globalchange.gov https://nca2018.globalchange.gov/chapter/3 [accessed 26 March 2021].
2. Prein AF, Rasmussen RM, Ikeda K, Liu C, Clark MP, Holland GJ. 2017. The future intensification of hourly precipitation extremes. Nat Clim Chang 7(1):48–52, https://doi.org/10.1038/nclimate3168.
3. Smith KR, Woodword A, Campbell-Lendrum D, et al. 2014. Human health: Impacts, adaptation, and co-benefits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press, 709–754.
4. Carlton EJ, Eisenberg JNS, Goldstick J, Cevallos W, Trostle J, Levy K. 2014. Heavy rainfall events and diarrhea incidence: the role of social and environmental factors. Am J Epidemiol 179(3):344–352, PMID: 24256618, https://doi.org/10.1093/aje/kwt279.
5. Jagai JS, Li Q, Wang S, Messier KP, Wade TJ, Hilborn ED. 2015. Extreme precipitation and emergency room visits for gastrointestinal illness in areas with and without combined sewer systems: an analysis of Massachusetts data, 2003–2007. Environ Health Perspect 123(9):873–879, PMID: 25855939, https://doi.org/10.1289/ehp.1408971.
6. Kraay ANM, Man O, Levy MC, Levy K, Ionides E, Eisenberg JNS. 2020. Understanding the impact of rainfall on diarrhea: testing the concentration-dilution hypothesis using a systematic review and meta-Analysis. Environ Health Perspect 128(12):126001, PMID: 33284047, https://doi.org/10.1289/EHP6181.
7. Lee D, Chang HH, Sarnat SE, Levy K. 2019. Precipitation and salmonellosis incidence in Georgia, USA: interactions between extreme rainfall events and antecedent rainfall conditions. Environ Health Perspect 127(9):97005, PMID: 31536392, https://doi.org/10.1289/EHP4621.
8. Drayna P, McLellan SL, Simpson P, Li SH, Gorelick MH. 2010. Association between rainfall and pediatric emergency department visits for acute gastrointestinal illness. Environ Health Perspect 118(10):1439–1443, PMID: 20515725, https://doi.org/10.1289/ehp.0901671.
9. Wade TJ, Lin CJ, Jagai JS, Hilborn ED. 2014. Flooding and emergency room visits for gastrointestinal illness in Massachusetts: a case-crossover study. PLoS One 9(10):e110474, PMID: 25329916, https://doi.org/10.1371/journal.pone.0110474.
10. U.S. Environmental Protection Agency. 2020. Combined sewer overflow frequent questions. National Pollutant Discharge Elimination System (NPDES). https://www.epa.gov/npdes/combined-sewer-overflow-frequent-questions [accessed 26 April 2020].
11. Olds HT, Corsi SR, Dila DK, Halmo KM, Bootsma MJ, McLellan SL. 2018. High levels of sewage contamination released from urban areas after storm events: a quantitative survey with sewage specific bacterial indicators. PLoS Med 15(7):e1002614, PMID: 30040843, https://doi.org/10.1371/journal.pmed.1002614.
12. Bi EG, Monette F, Gachon P, Gaspéri J, Perrodin Y. 2015. Quantitative and qualitative assessment of the impact of climate change on a combined sewer overflow and its receiving water body. Environ Sci Pollut Res Int 22(15):11905–11921, PMID: 25869430, https://doi.org/10.1007/s11356-015-4411-0.
13. Lund A, McMillan J, Kelly R, Jabbarzadeh S, Mead DG, Burkot TR, et al. 2014. Long term impacts of combined sewer overflow remediation on water quality and population dynamics of Culex quinquefasciatus, the main urban West Nile virus vector in Atlanta, GA. Environ Res 129:20–26, PMID: 24528998, https://doi.org/10.1016/j.envres.2013.12.008.
14. Passerat J, Ouattara NK, Mouchel JM, Rocher V, Servais P. 2011. Impact of an intense combined sewer overflow event on the microbiological water quality of the seine river. Water Res 45(2):893–903, PMID: 20934197, https://doi.org/10.1016/j.watres.2010.09.024.
15. McGinnis S, Spencer S, Firnstahl A, Stokdyk J, Borchardt M, McCarthy DT, et al. 2018. Human Bacteroides and total coliforms as indicators of recent combined sewer overflows and rain events in urban creeks. Sci Total Environ 630:967–976, PMID: 29554782, https://doi.org/10.1016/j.scitotenv.2018.02.108.
16. Donovan E, Unice K, Roberts JD, Harris M, Finley B. 2008. Risk of gastrointestinal disease associated with exposure to pathogens in the water of the Lower Passaic River. Appl Environ Microbiol 74(4):994–1003, PMID: 18156342, https://doi.org/10.1128/AEM.00601-07.
17. Honda R, Tachi C, Yasuda K, Hirata T, Noguchi M, Hara-Yamamura H, et al. 2020. Estimated discharge of antibiotic-resistant bacteria from combined sewer overflows of urban sewage system. NPJ Clean Water 3(1):1–7, https://doi.org/10.1038/s41545-020-0059-5.
18. Aulenbach BT, McKee AM. 2020. Monitoring and Real-Time Modeling of Escherichia Coli Bacteria for the Chattahoochee River, Chattahoochee

River National Recreation Area, Georgia, 2000–2019. https://doi.org/10.3133/ofr20201048.
19. DeFlorio-Barker S, Wing C, Jones RM, Dorevitch S. 2018. Estimate of incidence and cost of recreational waterborne illness on United States surface waters. Environ Health 17(1):3, PMID: 29316937, https://doi.org/10.1186/s12940-017-0347-9.
20. Chattahoochee Riverkeeper. Chattahoochee Riverkeeper Celebrates 25 Years of Stewardship. https://chattahoochee.org/wp-content/uploads/2019/03/CRK_25_YEAR_REPORT_DIGITAL_FINAL.pdf [accessed 26 April 2020].
21. Brokamp C, Beck AF, Muglia L, Ryan P. 2017. Combined sewer overflow events and childhood emergency department visits: a case-crossover study. Sci Total Environ 607-608:1180–1187, PMID: 28732397, https://doi.org/10.1016/j.scitotenv.2017.07.104.
22. Redman RL, Nenn CA, Eastwood D, Gorelick MH. 2007. Pediatric emergency department visits for diarrheal illness increased after release of undertreated sewage. Pediatrics 120(6):e1472–e1475, PMID: 18055664, https://doi.org/10.1542/peds.2007-0283.
23. City of Atlanta, Department of Watershed Management. Consent Decree Document Repository. https://drive.google.com/drive/folders/16Q-CJLAeVRg6h2LHtM9q6jR0-Gh31P-FR [accessed 1 November 2019].
24. Clean Water Atlanta. CSO Project Milestones. https://cleanwateratlanta.h2o4atl.com/index.php/cso-projects/ [accessed 1 November 2019].
25. Abrams JY, Klein M, Henneman LRF, Sarnat SE, Chang HH, Strickland MJ, et al. 2019. Impact of air pollution control policies on cardiorespiratory emergency department visits, Atlanta, GA, 1999–2013. Environ Int 126:627–634, PMID: 30856450, https://doi.org/10.1016/j.envint.2019.01.052.
26. Levy K, Klein M, Sarnat SE, Panwhar S, Huttinger A, Tolbert P, et al. 2016. Refined assessment of associations between drinking water residence time and emergency department visits for gastrointestinal illness in metro Atlanta, Georgia. J Water Health 14(4):672–681, PMID: 27441862, https://doi.org/10.2166/wh.2016.178.
27. O'Lenick CR, Winquist A, Mulholland JA, Friberg MD, Chang HH, Kramer MR, et al. 2017. Assessment of neighbourhood-level socioeconomic status as a modifier of air pollution-asthma associations among children in Atlanta. J Epidemiol Community Health 71(2):129–136, PMID: 27422981, https://doi.org/10.1136/jech-2015-206530.
28. Winquist A, Grundstein A, Chang HH, Hess J, Sarnat SE. 2016. Warm season temperatures and emergency department visits in Atlanta, Georgia. Environ Res 147:314–323, PMID: 26922412, https://doi.org/10.1016/j.envres.2016.02.022.
29. Ye D, Klein M, Mulholland JA, Russell AG, Weber R, Edgerton ES, et al. 2018. Estimating acute cardiovascular effects of ambient $PM_{2.5}$ metals. Environ Health Perspect 126(2):027007, PMID: 29467104, https://doi.org/10.1289/EHP2182.
30. U.S. Census Bureau. 2011. American Community Survey, 5-year summary file. https://www.census.gov/programs-surveys/acs/data/summary-file.2011.html [accessed 20 February 2020].
31. U.S. Centers for Disease Control and Prevention. Cryptosporidium—General Information for the Public. https://www.cdc.gov/parasites/crypto/general-info.html [accessed 26 April 2020].
32. Department of Ecology, State of Washington. 2020. Seattle and King County Fined for Sewer Overflow Violations. https://ecology.wa.gov/About-us/Who-we-are/News/2020/Dec-18-King-County-and-Seattle-CSO [accessed 26 January 2022].
33. U.S. Centers for Disease Control and Prevention. The Symptoms of Norovirus. https://www.cdc.gov/norovirus/about/symptoms.html [accessed 26 March 2021].
34. Stalsberg R, Pedersen AV. 2018. Are differences in physical activity across socioeconomic groups associated with choice of physical activity variables to report? Int J Environ Res Public Health 15(5):922, PMID: 29734745, https://doi.org/10.3390/ijerph15050922.
35. Pollack CE, Du S, Blackford AL, Herring B. 2019. Experiment to decrease neighborhood poverty had limited effects on emergency department use. Health Aff (Millwood) 38(9):1442–1450, PMID: 31479355, https://doi.org/10.1377/hlthaff.2019.00452.
36. Levy K, Woster AP, Goldstein RS, Carlton EJ. 2016. Untangling the impacts of climate change on waterborne diseases: a systematic review of relationships between diarrheal diseases and temperature, rainfall, flooding, and drought. Environ Sci Technol 50(10):4905–4922, PMID: 27058059, https://doi.org/10.1021/acs.est.5b06186.
37. U.S. Geological Survey. BacteriALERT Realtime Monitoring. https://www2.usgs.gov/water/southatlantic/ga/bacteria/ [accessed 9 August 2021].
38. Nwachuku N, Gerba CP. 2006. Health risks of enteric viral infections in children. Rev Environ Contam Toxicol 186:1–56, PMID: 16676900, https://doi.org/10.1007/0-387-32883-1_1.
39. Kaiser KL, Barry Hultquist T, Chen LW. 2016. Maternal Health-seeking on behalf of low-income children. Public Health Nurs 33(1):21–31, PMID: 26365293, https://doi.org/10.1111/phn.12228.
40. Mooney SJ, Richards CA, Rundle AG. 2014. There goes the neighborhood effect: bias due to non-differential measurement error in the construction of neighborhood contextual measures. Epidemiology 25(4):528–535, PMID: 24815303, https://doi.org/10.1097/EDE.0000000000000113.
41. Levy MC, Collender PA, Carlton EJ, Chang HH, Strickland MJ, Eisenberg JNS, et al. 2019. Spatiotemporal error in rainfall data: consequences for epidemiologic analysis of waterborne diseases. Am J Epidemiol 188(5):950–959, PMID: 30689681, https://doi.org/10.1093/aje/kwz010.
42. Rostami S, He J, Hassan QK. 2018. Riverine water quality response to precipitation and its change. Environments 5(1):8, https://doi.org/10.3390/environments5010008.